

# THERMAL CONTROL TECHNOLOGIES FOR COMPLEX SPACECRAFT

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## ABSTRACT

Thermal control is a generic need for all spacecraft. In response to ever more demanding science and exploration requirements, spacecraft are becoming ever more complex, and hence their thermal control systems must evolve. This paper briefly discusses the process of technology development, the state-of-the-art in thermal control, recent experiences with on-orbit two-phase systems, and the emerging thermal control technologies to meet these evolving needs. Some "lessons learned" based on experience with on-orbit systems are also presented.

**KEY WORDS:** Advanced thermal control, capillary pumped loops, loop heat pipes, heat pumps, cryogenic, moon

## 1. INTRODUCTION

Scientific and exploration goals continually drive the need for better spacecraft and instruments. The data and knowledge gained by one mission inevitably leads to more questions which can only be answered by more advanced spacecraft with higher performance, improved resolution, tighter pointing accuracy, increased sensitivity, and the ability to look into new parts on the electromagnetic spectrum. In the past major improvements for science missions were largely possible through new sensor technology alone. However, it is increasingly obvious that future advances will rely heavily on technology improvements in a wide range of areas, and especially in thermal management.

The implementation approach for thermal control in spacecraft is changing. Traditionally, thermal management was accomplished by discrete devices, such as electrical heaters, multi-layer insulation, and specialized radiative coatings which were selected based on a mathematical analysis of

the effect on a known environment and specified operating conditions. Spacecraft operating conditions were normally rather broad (plus or minus 20 to 30 °C) and power levels were low (in the 10's to 100's of Watts), and such simple techniques worked well enough. However, modern spacecraft and instruments are requiring much tighter temperature control (to a 1/10<sup>th</sup> °C) over large areas (several square meters), and possibly require rejection of several kW of waste heat. Planned exploration missions will be going to locations with very difficult thermal environments (e.g., the moon, Mars, and near the sun) and may include propulsion, power, habitats, instrumentation, and other subsystems that will place very demanding requirements on the thermal control subsystem. New technologies are required to meet these needs.

Thermal control subsystems are also becoming much more integrated with other subsystems on a spacecraft or instrument. They can no longer be developed in isolation or at the end of a spacecraft design cycle, but must be done concurrently with other subsystems. This situation is a natural evolution driven by need to improve

performance and minimize mass/parasitic power of all support subsystems. The lower the mass and parasitic power of such support equipment, the greater the payload that can be accommodated.

It is also evident that identifying just what new thermal control technology is needed for such complex systems, securing funding for its development, and overcoming the obstacles to introducing such new technology is a most challenging task. This challenge is generally comparable to the technical challenge. *This perspective has profound implications for both determining just what new technology should be developed and how it is to be integrated into a spacecraft.*

The Goddard Space Flight Center (GSFC) is primarily tasked to focus on robotic spacecraft and instruments, or the human tended servicing of such equipment. Hence this paper addresses the thermal control subsystems of such spacecraft and instruments. Goddard is the National Aeronautics and Space Administration's (NASA) lead center for the Earth Science Enterprise, has a very significant involvement in the Space Science Enterprise, and an emerging role in the new Exploration Initiative. Most recently NASA Headquarters asked GSFC to assume management responsibility for the Robotic Lunar Exploration Program. The first planned lunar mission is an orbiter in 2008, to be quickly followed by a lander in 2009. Early analytical studies indicate that thermal control will be a significant issue for many these exploration missions, as well as numerous planned future science missions.

## **2. PROCESS OF TECHNOLOGY INTRODUCTION**

One might imagine a logical process for technology development in which needs are first identified and independently verified, then costs and schedules are established, and finally appropriate funding is provided to bring the technology vision to reality.

Unfortunately, however, this scenario virtually never happens for a variety of practical reasons:

- 1) The principal driver for technology development is the mission and its science or exploration goals. These goals are, by necessity, increasingly vague the further out in time the mission is. This is principally due to a tradeoff between what is technically possible, the cost to fly a proposed mission, and the perceived value of the science/exploration. Often there are alternative means of collecting new science data or exploring. For example, one might use a chronograph or an interferometer in the search for terrestrial-like planets in other solar systems, and these different mission concepts will require very different thermal control technologies.
- 2) The perceived value of various mission concepts changes over time. One new discovery, or exploration achievement, may lead to new understandings that supplant previously perceived values.
- 3) Developing practical technology is not a given. Invariably there are unanticipated technical difficulties, interactions with other subsystems, and various subtleties that require extra time and money to overcome. Thus, if one is trying to develop new technology under a limited budget and firm schedule - say to support a specific planned mission - there is the very real risk of not being successful.
- 4) Other drivers, such as the mission itself, specific science and exploration goals, the budget, or other technical subsystems upon which a

technology is dependent, may all change over time.

- 5) Technology is often perceived as a threat from a variety of viewpoints: technical performance, schedule, and cost. Program Managers, who are responsible for mission success, often do not want to be the first to fly a new technology; they want proof of probable success. Hence, they are commonly reluctant to incorporate new and unproven technology.

The process of technology development may be characterized as trying to hit a moving target (the mission goals) with a wobbly arrow (the new technology). Both the end point and the means of getting there are somewhat unknown. *Nevertheless, the common phrase "technology is our future" is certainly true.* Technology enables new science and new exploration. The challenge for technologists is to realistically perceive what is possible with a given schedule and budget, convince others of its worth, and then bring it to fruition.

Given the difficulty of this process of technology development and introduction, it is often best to develop multiple technologies that have relatively broad applicability. This less focused approach provides a flexible set of technologies to meet a broad set of problems. Securing funding is a typically a multi-step process with institutional type funding supporting the early efforts. Once a technology has developed to a point where it appears promising, then support can be sought from flight programs. However, the transition from early development to flight program support is often very difficult.

### 3. STATE-OF-THE-ART IN SPACECRAFT THERMAL CONTROL

The most advanced thermal control technologies currently employed in operational spacecraft are two-phase loops, such as Capillary Pumped Loops (CPLs) and Loop Heat Pipes (LHPs). These technologies clearly represent the major thermal control innovation of the last decade as they offer orders of magnitude improvement over traditional heat pipes (Ku, 1999; Swanson, 2004; Birur, 2004). CPLs and LHPs are in many ways very similar, but do have distinct characteristics (Butler, 2002). These self-contained, two-phase devices utilize the latent heat of evaporation/condensation of a fluid to acquire and transport waste heat long distances with negligible temperature drop. See Figure 1.

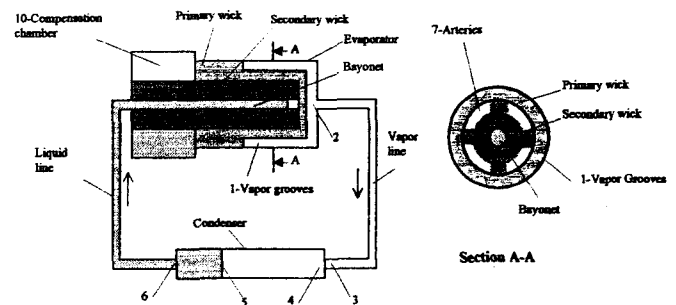


Figure 1. Generic Loop Heat Pipe

Both CPLs and LHPs consist of a closed loop with a porous evaporator, or wick, at one end and a condenser at the other. The wick may be a plastic such as polyethylene or a metal. A pair of smooth wall tubes connects the evaporator and condenser. The loop is partially filled with a refrigerant, typically ammonia or propylene for applications near room temperature. Waste heat is applied to the wick (which is saturated with the refrigerant) and is absorbed by evaporation of the refrigerant. A fluid reservoir is attached to the liquid line to accommodate fluctuating fluid inventories and also to provide a source of constant pressure against the refrigerant, thus locking the loop at a constant temperature. This temperature control is typically accomplished by cold biasing the reservoir and using make-up heaters to bring the

temperature up to the desired “set point”. Since the internal pressure of the loop is held constant, evaporation and condensation occur at a nearly constant temperature that is determined by the basic thermophysical properties of the refrigerant. Hence, the control set point essentially establishes isothermal conditions throughout the loop.

The resulting vapor is transported, via the non-wicked connecting tubing, to the condenser (i.e., radiator) where it is condensed back to a liquid. This condensation releases the waste heat that is then rejected to space via radiation. The liquid is then returned to the wick via a separate tube, and the process continues. A surface tension developed at the vapor/liquid interface across the menisci on the porous wick provides the pumping force to circulate the fluid. The system thus operates passively and requires no mechanical pump or flow control devices and is free from vibrations. Since it is a two-phase device a CPL or LPH can provide a very stable and constant interface temperature regardless of changes in the heat load and/or radiator sink condition.

CPLs and LHPs can operate stably and at constant temperature regardless of changing heat loads and/or thermal sink. Operationally, their most difficult issue is in startup since this involves getting the liquid and vapor to the proper locations throughout the loop (Ku, 1995).

#### **4. ON-ORBIT EXPERIENCE WITH TWO-PHASE LOOPS**

The development of CPLs was initiated in the United States in the early 1980's. The first flight experiments conducted on the Space Shuttle in 1986 (Ku, 1986). LHP technology, which is similar but distinct from CPL technology, was initiated and developed in Russia (Maidanik, 1992). After extensive ground testing and additional flight experiments during the

early 1990's, CPLs and LHPs finally reached technology readiness for space applications.

The first operational CPL was NASA's TERRA spacecraft, the first Earth Observing System (EOS) platform, which was launched in December of 1999 (Chalmers, 2000). The TERRA spacecraft is depicted in Figure 2. TERRA has three scientific instruments that use CPLs for tight temperature control. Each instrument has two fully redundant, ammonia based, CPLs and several traditional heat pipes and electrical heaters. While each instrument has redundant CPLs, at any given time only one is active. Instrument waste heat loads vary from 25 to 264W.

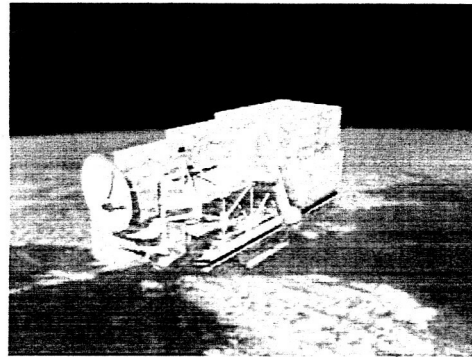


Figure 2. Conceptual Image of TERRA

In the 4+ years since TERRA was launched all three operating CPLs have provided a stable interface temperature as required by the instrument, under all modes of spacecraft operation, heat load, and environmental sink conditions (Ku, 2004). The TERRA CPLs have demonstrated an on-orbit capability to maintain temperature control within  $\pm 0.1^{\circ}\text{C}$ . On two of the instruments the CPL was started easily, but on one, the TIR instrument, there was some minor difficulty in maintaining operations. On January 7, 2000, one of TIR's CPL loops was started using a standard start-up procedure. However, the loop deprimed after just 62 hours. The instrument's second CPL was started on January 13, 2000 using the same standard start-up procedure.



Unfortunately, this second loop also deprimed within about 2 days. On January 19, 2000, a back-up starting procedure, which was more elaborate, was attempted. This involved clearing the evaporator's vapor spaces and the vapor line of liquid prior to applying heat to the saturated wick. Provisions for this back-up starting procedure had been incorporated into the design of Terra's CPLs since it had been established that start-up was by far the most stressful event that a CPL will face. The back-up starting procedure was successful, and the loop operated well until February 20, 2000, when it again deprimed. It was noted that this last deprime occurred after four successive, 300-second, orbit inclination burns that transpired over a one-week period. These burns created an artificial gravity vector that unfortunately was aligned with the long axis of the reservoir. Such body forces are believed to have significantly contributed to this last deprime. On February 24, 2000 the TIR CPL was again restarted. To promote greater refrigerant flow, which tends to stabilize CPL operation, beginning in March some additional heat (from electrical heaters) was applied to the evaporator. The TIR CPL has been successfully operating in this mode since then.

An additional benefit of this two-phase technology is its ability to change set point temperature upon command. In July of 2001 one of the TERRA instruments that is thermally conditioned by a CPL, the ASTER-SWIR instrument, began to experience excessive temperatures. This instrument has mechanical cryocoolers that, for unclear reasons, began to draw more power and overheat. To accommodate this temperature growth, the temperature set point of its CPL was lowered by  $4.5^{\circ}\text{C}$  thus extending the instrument's life. In January of 2003 the cryocoolers were again reaching an unacceptable temperature, so a similar procedure was followed and the CPL set point was adjusted (lowered by  $3.0^{\circ}\text{C}$ ), thus further extending the instrument's life (Ku, 2004).

Another recent CPL application is on the Hubble Space Telescope (HST), which has a CPL to remove heat from the new cryocooler attached to an instrument, the Near Infrared Camera Multi-Object Spectrometer (NICMOS), which is located inside the aft shroud (McIntosh, 1998). The original NICMOS instrument had been installed on an earlier HST Servicing Mission. NICMOS was designed to view space in infrared wavelengths, and thus required a sensor cryogenically cooled to about 60 to 70 K. This was accomplished by use of a dewar with a stored cryogen. NICMOS collected excellent science, but the dewar became prematurely depleted and the instrument had to be shut off. A concept to revive the instrument by adding a mechanical cryo-cooler was then developed. This mechanical cryo-cooler, a reverse Brayton cycle machine, had the capacity to apply about 8W of cooling to the existing dewar, but in so doing generated 300-400W of waste heat. A CPL was proposed to acquire this waste heat from inside the aft shroud of the Hubble Space Telescope and transport it to the exterior for rejection to space. See Figure 3. This concept promised to rejuvenate the sensor and provide much longer life.

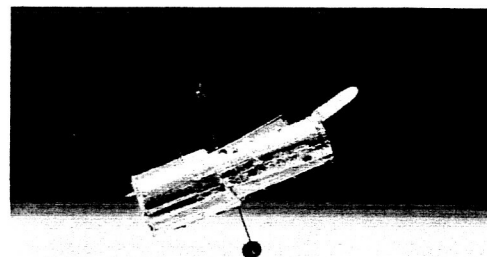


Figure 3. Hubble Space Telescope in Orbit

On a recent shuttle mission, HST/Servicing Mission-3B in March of 2002, this instrument rescue concept was implemented.

The astronauts installed a CPL evaporator through the bottom of HST's aft shroud, attached it to the new NICMOS cryo-cooler, and then attached a new radiator to the external handrails. Since Figure 4 depicts a photograph of an astronaut installing the external radiator. Installation proceeded smoothly as planned, and the new NICMOS cooling system soon began operating. Flight data has verified that the new cryo-cooler and CPL cooling system has successfully reduced the temperature of the NICMOS sensors to approximately 70K, which is the optimum temperature needed for operation (Buchko, 2002). The cryocooler/CPL system has operated smoothly since then and has been able to maintain very tight temperature control (to  $\pm 0.1$  °C). This is despite the fact that HST's external radiators are continually reorienting their thermal sink exposure as the spacecraft circles the earth and points to different astronomical objects. The system employs a sophisticated control algorithm to continually change the CPL's operational parameters in response to thermal load and available thermal sink conditions. In fact, by use of the new cryo-cooler/CPL, which can provide an adjustable set point, the NICMOS sensor can now operate at a more favorable temperature for better science.

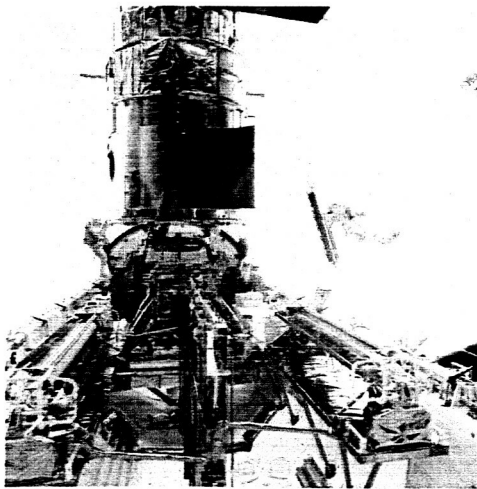


Figure 4. Astronaut Installing CPL on HST  
The only on-orbit LHP application on a NASA spacecraft is on the Geoscience Laser

Altimetry System (GLAS) instrument on the ICESAT spacecraft (Baker, 2004). Others are in development, such as the TES instrument on the AURA spacecraft and the BAT instrument on the SWIFT spacecraft, but as of this writing these spacecraft have not yet been launched. The ICESAT spacecraft was launched in February of 2003 and successfully turned on shortly thereafter. GLAS, its only instrument, is a laser altimeter operating at room temperature with approximately 120 watts thermal load. Its primary purpose is to measure the thickness of the polar ice sheets. The GLAS LHP application is depicted in Figure 5.

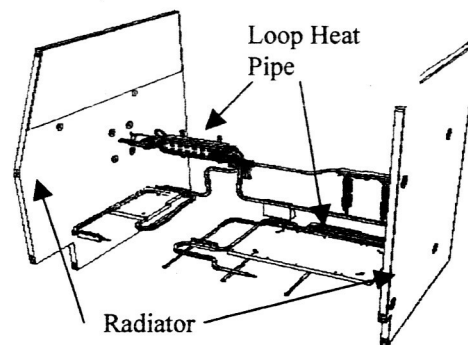


Figure 5. LHPs on GLAS

GLAS actually has two LHPs, one on the laser system and the other on the electronics. The laser LHP has a 120W heat load while the electronics provides about 200W of heat to its own LHP. Both LHPs require about 4 to 5W to maintain temperature control to  $\pm 0.1$  °C. The temperature control point can be varied, and this capability proved to be very useful in aligning the optical system (via coefficient of thermal expansion effects). Propylene was used as a heat transfer fluid since the radiator can get very cold, less than -130 °C, and ammonia would freeze. Flexible lines between the evaporators and radiators allowed ease of installation, vibration isolation, and facilitated ground testing.

Once in orbit the GLAS LHPs started easily and operated smoothly with no significant differences between ground and flight

operation. However, in September of 2003 a flight anomaly occurred during a yaw maneuver to a more transient attitude. The LHP on the electronics first showed some temperature spikes and then entered a slow circulation mode that could not be reversed by applying additional heater power. See Figure 6. It was necessary to turn off the loop and power down the instrument. The LHP was restarted by allowing it to cool to its survival range, letting the thermostat survival heaters cycle to push fluid in and out of the evaporator core to clear it of any possible vapor, and then applying starter heater power at a lower than normal temperature set point. The restarted LHPs then operated nominally until April of 2004 when similar precursor temperature spikes appeared. As of this writing the loop is still operating without any additional loss of control.

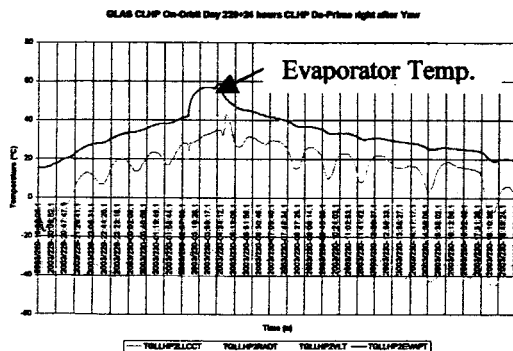


Figure 6. Temperature Spike on GLAS

The cause of this anomaly was, and remains, unclear. It appears to be related to the absence of sufficient liquid in the evaporator core, but this could be caused by several factors. Initial suspicions focused on unusual thermophysics caused during the yaw maneuvers, and it was felt that maximizing the fluid inventory in the evaporator would solve the problem. Non-condensable gas was also considered as a possibility. However, the recurrence of symptoms several months later leads to increased suspicions of a slow fluid leak (from a micrometeroid penetration, cracked weld, or other problem). Unfortunately, while this

LHP has more flight instrumentation than would normally be accommodated for traditional “housekeeping” functions, with the available suite of GLAS instrumentation we are not able to absolutely verify the cause of this anomaly. The best “fix” to the problem is to maximize fluid in the evaporator by applying additional heater power to the evaporator and keeping the set point as low as possible, consistent with science needs. Ideally one would like to use a backup LPH, but this spacecraft was designed and built under guidelines that specified a low cost, non-redundant approach.

All current United States CPL and LHP flight applications involve the use of a single evaporator. This approach is somewhat limiting. To address this issue, a flight experiment, CAPL 3 was flown on the Shuttle in December of 2001 (Ottenstein, 2002). A view of CAPL 3 from the International Space Station is shown in Figure 7. The CAPL 3 experiment successfully demonstrated the use of parallel evaporators with heat load sharing between them. It had four, 2.5 cm diameter evaporators with polyethylene wicks, a separate starter pump, eight direct condenser lines plumbed in parallel, and a back pressure flow regulator to facilitate clearing of the evaporators during startup. While in orbit CAPL 3 demonstrated reliable start-up (9 attempts, all successful), continuous operation for extended periods of time, high power to 1500 W, extended low power at 100W, and heat load sharing between the evaporators. Overall the flight experiment was thus considered to be quite successful. It is also noteworthy that although the experiment was held in storage, in a fully charged state, for 2 years, testing indicated no evidence of non-condensable gas generation effects.

While there are no cryogenic two-phase loops in orbit, the perceived need for such capability in the future has spurred technology development efforts. The basic designs are similar to ammonia/propylene

based systems, but with special accommodations for cryogenic operation. For such applications the operating fluid (nitrogen, neon, hydrogen, etc.) will be in a supercritical state, and typically at high pressure, prior to startup. This situation complicates the startup process.

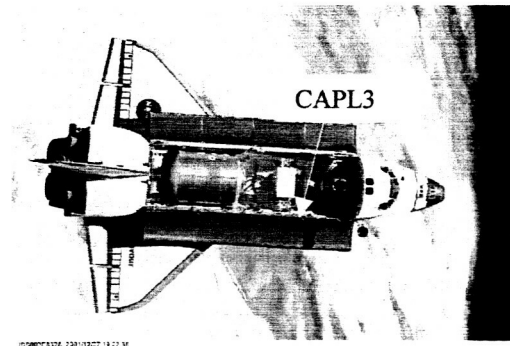


Figure 7. CAPL3 Experiment on Shuttle

A cryogenic CPL was flown on a Space Shuttle flight, STS-95, in 1998 (Bugby, 1999). The test unit used nitrogen as a working fluid, weighed 191 grams, and had an effective transport length of 0.25 meters. It successfully demonstrated reliable start-up and heat transport of over 2.5 watts at approximately 80K. While the system demonstrated transport on the ground at over 10 watts, the flight experiment was limited due to the available cold sink. Other cryogenic loops with neon and hydrogen have been built and ground tested with good results.

These flight experiences with two-phase loops have provided some “lessons learned” useful for future flight system designs.

- Two-phase loops, such as CPLs and LHPs, can perform superbly in space flight applications
- Both types of loops can provide very tight temperature control and transport significant quantities of waste heat over long distances

- The ability to change set temperature on-orbit can have wide ranging benefits
- Flexible transport lines are very helpful for ground testing and integration
- Either ammonia or propylene can be used for room temperature applications, with propylene having a much lower freezing point
- Parasitic heat needed for temperature control is generally negligible
- Backup systems, such as redundant loops, alternative startup techniques, and redundant heaters are very helpful if cost and weight permit
- Starter heaters are a highly reliable and simple solution, both for startup and as a supplemental source of heat to promote smooth loop operation
- Ground and in-flight data correlate well
- Loop startup is generally easier on orbit
- While it cannot be ruled out, there is no firm evidence that non-condensable gas generation occurs and/or is a problem
- Flight loops should have as much instrumentation and operational flexibility as possible

As these flight applications and experiments demonstrate, ambient temperature CPLs and LHPs have reached a point of flight maturity. This is not to suggest that additional technology development is not needed, or that no implementation issues remain. For example, current issues with CPL/LHP technology include the need for a significant amount of custom engineering to design and integrate the technology, preconditioning of the loop is often required prior to start-up, and some of the hardware is larger than convenient. Irrespective of

these concerns, current two-phase technologies can and have been reliably applied to operational spacecraft. Two-phase technology offers significant design flexibility, tight temperature control, broad heat transport capacity, diode function and isothermalization. Their performance is unmatched by any other technology.

## **5. TECHNOLOGY NEEDS FOR FUTURE SPACE MISSIONS**

While current two-phase thermal control technology has offered at least an order-of-magnitude improvement over the previous state-of-the-art, additional technology development is not only possible, but also necessary. Such development will primarily be driven the needs of the missions they support; the key question is to define those needs far enough in advance to allow time for the technology to be developed for when it is needed.

Future NASA missions will focus on exploration and advanced science, both of which will drive the need for new thermal control technology (Martins, 2004). The type of thermal control system (TCS) employed is a function of the application. Key parameters driving the design of the TCS include: power level, control temperature, degree of temperature control, heat flux intensity, transport distance, and effective thermal sink to which the heat is rejected.

A prime example of the type of new TCS technology needed include systems that can acquire, transport and efficiently reject large quantities of waste heat from a propulsion or power system. This may involve both high power levels (in the 10s of KW to MWs) and high flux (above 100 W/cm<sup>2</sup>). High power lasers or other electronic equipment may also have this high flux problem. Some applications will also involve very high temperatures. Advanced heat transport systems, such as two-phase loops, and

efficient, lightweight, puncture resistant radiators will be needed to transport and reject high power loads. Spray cooling or other advanced heat acquisition techniques may be needed for high fluxes. The control temperature of such systems may vary from near room temperature to the 100's of °C, and this may drive the need for water, or even liquid metal based, two-phase devices. Up to about 250 °C, existing two-phase technology could be used by simply using water as the refrigerant. This would involve somewhat higher pressures than for typical ammonia based systems, but the basic thermophysics is the same.

Another situation that will need some sort of new heat rejection technology is missions where the thermal sink is near or above the operational control temperature. The moon, during mid-day, is one such situation. In space the only practical way to ultimately reject heat is via radiation, which is proportional to the 4<sup>th</sup> power of the difference in temperature between the source and thermal sink. During lunar mid-day a standard radiator will "see" the sun and/or the hot regolith, both of which are hotter than room temperature (Simonson, 1988 and Swanson, 1990). Hence, some type of new TCS is needed: prime examples are efficient, space qualified, low mass heat pumps or advanced radiators that can avoid views to these hot sinks. This problem is particularly acute for mobile facilities (such as surface rovers, in-situ mining equipment, etc.) that will vary the exposure of their radiators in an uncontrolled manner.

Yet another situation envisioned for future exploration missions involves complex equipment, such as spacesuits, robots, large rover vehicles, and in-situ resource utilization equipment. Such equipment may have multiple heat loads zones that turn on/off at random intervals, and also have multiple radiators. Due to the constantly varying solar and thermal sink exposure of such radiators it will be difficult to efficiently reject heat. Hence, what is desired is a TCS that can acquire heat from

multiple zones independent of each other, control temperature within a reasonable band, and yet reject such waste heat to any available heat sink. Heat load sharing (from warm load zones to those needing makeup heat) would also be desirable. Advanced CPLs or LPHs, possibly with the addition of a mechanical pump, will be needed to address such applications. In addition, to modulate the efficiency of the radiators, specialized coatings that could vary the emissivity and/or absorptivity of the radiators in a controlled fashion would be highly desirable.

Spacecraft designs for future NASA science missions are becoming increasingly complex. Many of the most interesting science objectives are driving a push towards increasingly large and cold optics. For example, missions to study the creation of the universe, or to look for extraterrestrial earth-like planets, require very large aperture optics (to 10 meters in diameter) that may also need to be exceptionally cold (to 4 Kelvin). In order to keep the signal to noise ratio sufficiently low when viewing objects in the mid to far infrared and sub-millimeter region of the spectra, the entire optical path must be kept very cold. For example, the optics for the James Webb Space Telescope must be in the 50 K or below range (Parrish, 2003).

Conceptual designs for even more advanced science concepts call for optical paths as cold as a few degrees Kelvin. Providing cooling of large optics to such levels, for such large areas, will truly be a very challenging task. Figure 8 depicts one concept of an integrated thermal control system that includes a sunshield for long term protection from solar radiation, high conductivity substrate on the mirror for thermal stabilization, cryogenic heat pipes and LHPs for heat transport, and active cryo-coolers for ultimate heat rejection.

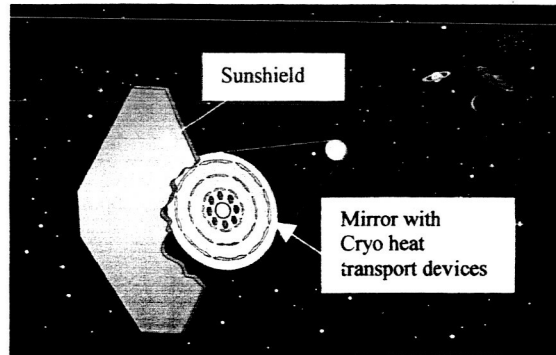


Figure 8. Large Cryogenic Telescope

Such missions also require long observational exposure times, which necessitates extreme mechanical stability and ultra tight pointing. Many instruments now require temperature control to  $\pm 1^\circ\text{C}$  over areas of a square meter or so, and with increasing power levels and larger optics this issue will become an even more demanding challenge.

Hence, both the new Exploration Initiative missions and the proposed science missions will drive the need for increasingly sophisticated and capable thermal control technology.

## 6. EMERGING TWO-PHASE THERMAL CONTROL TECHNOLOGIES

In response to these perceived needs NASA/Goddard has been pursuing development of a variety of thermal control technologies. Almost all of these new technologies are useful for both exploration and science missions, while a few are more directed to one application or the other. Current efforts include:

- Heat pump designs extrapolated from conventional vapor compression, terrestrial based designs



- Spray cooling for high heat fluxes; see Figure 9
- Multi-evaporator, multi-condenser, two-phase heat transport loops; see Figure 10
- Cryogenic (3 K to 80 K) heat transport devices (loop heat pipes, capillary pumped loops, etc.) for sensor and /or optics cooling which incorporate a diode function
- Advanced thermal control coatings such as variable emissive surfaces that permit adaptive, intelligent control of a radiator's capacity.
- Integrated structural, alignment, and thermal control concepts for very large structures.
- Thermal switches for cryogenic applications
- Advanced high conductivity materials, such as annealed polytic graphite, which may be suitable for cryogenic applications.

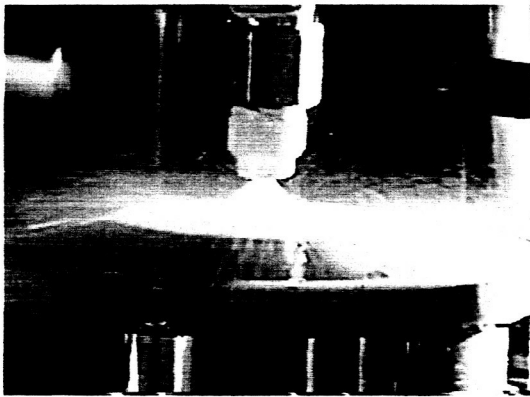


Figure 9. Spray Cooling on Hot Surface

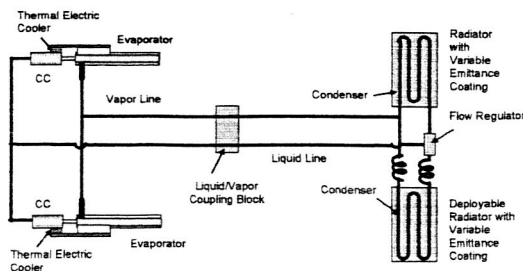


Figure 10. Multi-evaporator/condenser LHP

## 7. CONCLUSIONS

Two-phase, ambient temperature, single/multiple evaporator thermal control loops are now fully operational. Numerous examples of such applications are already in-orbit and several others are in assembly. Flight experience to date has been very satisfactory. This technology is proving itself to be highly versatile and offers performance capabilities unmatched by conventional thermal control technology.

In response to the perceived requirements of future missions, a variety of new thermal control technologies are being developed. These include technologies to allow heat rejection in a hot environment and modular/multifunctional two-phase loops to accommodate applications with multiple heat load zones and multiple radiators. Additional technologies actively being developed include cryogenic two-phase loops (down to 3K), thermal switches, ultra high thermal conductivity materials, and technologies to accommodate very high heat fluxes. Rich opportunities exist as these and other technologies offer increasing design options for the thermal engineer.

## NOMENCLATURE

C; degrees Centigrade  
 $\text{cm}^2$ ; centimeters squared  
 KW; kilowatts  
 MW; Megawatts  
 W; Watts

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